Probing the evolution of early-type galaxies using multi-colour number counts and redshift distributions

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ABSTRACT

We investigate pure luminosity evolution models for early-type (elliptical and S0) galaxies (i.e., no number density change or morphology transition), and examine whether these models are consistent with observed number counts in the B, I and K bands and redshift distributions of two samples of faint galaxies selected in the I and K bands. The models are characterized by the star formation time scale $\tau_{\rm SF}$ and the time $t_{\rm gw}$ when galactic wind blows in addition to several other conventional parameters. We find the single-burst model ($\tau_{\rm SF} = 0.1$ Gyr and $t_{\rm gw} = 0.353$ Gyr), which is known to reproduce the photometric properties of early-type galaxies in clusters, is inconsistent with redshift distributions of early-type galaxies in the field environment due to overpredictions of galaxies at $z \gtrsim 1.4$ even with strong extinction which is at work until $t_{\rm gw}$. In order for dust extinction to be more effective, we change $\tau_{\rm SF}$ and $t_{\rm gw}$ as free parameters, and find that models with $\tau_{\rm SF} \gtrsim 0.5$ Gyr and $t_{\rm gw} > 1.0$ Gyr can be made consistent with both the observed redshift distributions and number counts, if we introduce strong extinction ($E(B-V) \geq 1$ as a peak value). These results suggest that early-type galaxies in the field environment do not have the same evolutionary history as described by the single-burst model.

Key words: cosmology: observations — galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: formation — galaxies: photometry — galaxies: statistics

1 INTRODUCTION

How early-type galaxies were formed and evolved is a key issue in extragalactic astronomy which remains controversial. Evolution of early-type galaxies in clusters seems to be well expressed by the so-called single-burst model in which galaxies experience a star burst at the initial phase of their formation and then evolve passively without any subsequent star formation. For example, Ellis et al. (1997) found that the scatter in the colour-magnitude relation of early-type galaxies is quite small for $z \sim 0.5$ clusters, indicating that the major star formation ended at $z \gtrsim 3$ (See also Stanford, Eisenhardt & Dickinson 1998). Kodama et al. (1998) investigated the slope and zero-point of the colour-magnitude relation in 17 distant clusters with redshift $0.31 < z < 1.27$, and con-

strained the epoch of major star formation to $z > 2-4$. However, it is fairly controversial whether the single-burst model holds for early-type galaxies in the field environment. Abraham et al. (1999) analysed the spatially resolved colours of galaxies detected in the Hubble Deep Field (HDF; Williams et al. 1996) and argued that 40 % of early-type galaxies have experienced the major star formation at $z < 1$. Kodama, Bower & Bell (1999) obtained similar results on the basis of colour-magnitude diagram of HDF early-type galaxies. Franceschini et al. (1998) compared model spectra with a seven-colour broad band photometry of HDF early-type galaxies, and concluded that the major episodes of star formation building up typical M^* galaxies took place during $1 < z < 4$ for the deceleration parameter $q_0 = 0.5$ ($1 < z < 3$ for $q_0 = 0.15$). On the other hand, Bernardi et al. (1998)

showed, on the basis of the MgII-σ relation, that nearby early-type galaxies in clusters and in the field environment consist of the same stellar population, and claimed that the bulk of stars in the early-type galaxies had to form at $z \gtrsim 3$ in the field environment as well as in clusters.

In this paper, we first examine whether the single burst model reproduces both the observed number counts in the B, I and K bands and redshift distributions of two samples of HDF galaxies selected in the I and K bands. We will find that the single-burst model overpredicts galaxies at $z \gtrsim 1.4$ in redshift distribution even if the effect of dust extinction is taken into account during star formation. Following this result, we then introduce models which have longer periods of star formation than the single-burst model so that dust extinction work longer. We compare these models with the observations, and find that with a certain combination of parameters there are models whose predictions are consistent with the observations. Our study can be regarded as an extension of the work by Franceschini et al. (1998) in which they compared the single burst model and a model having a longer star formation period with K-band number counts and redshift distribution. We limit our discussion to so-called pure luminosity evolution models, because there is non-controversial evidence for number evolution or morphology evolution for early-type galaxies.

The structure of this paper is as follows. In §2, we describe the data used for our analysis, and in §3 we show how the local luminosity function is normalised. We compare the observed number counts and redshift distributions with models in §4. Our conclusions are given in §5. The cosmological parameters we have chosen to use throughout this paper are $(\Omega_0, \lambda_0, t_0) = (0.1, 0, 15~\mathrm{Gyr})$, unless otherwise stated, where Ω_0 is the density parameter, λ_0 is the cosmological constant, and t_0 is the present age of the universe (for this choice $h = 0.59$ where $H_0 \equiv 100h~\mathrm{km~s^{-1}~Mpc^{-1}}$). Note, however, that we have also examined models for two other cosmologies, $(\Omega_0, \lambda_0, t_0) = (1.0, 0, 13~\mathrm{Gyr})$ and $(0.1, 0.9, 15~\mathrm{Gyr})$, and found that main results do not change.

2   DESCRIPTION OF THE DATA

We use B-, I- and K-band number counts and redshift distributions of early-type galaxies. The B-band number count in the bright magnitude range is obtained using our mosaic CCD camera (Kashikawa et al. 1995) attached to the Las Campanas 1-m Telescope in 1995 October and to the 4.2-m William Herschel Telescope in 1996 April (4.30 deg^2 in total; hereafter MCCD data). The I- and K- band number counts in the bright magnitude range are taken from Huang, Cowie & Luppino (1998). Number counts in the faint magnitude range are taken from work based on the Hubble Space Telescope (HST) observations (Driver, Windhorst & Griffiths 1995; Driver et al. 1995; Glazebrook et al. 1995; Casertano et al. 1995; Abraham et al. 1996a,b; Odewahn et al. 1996; Driver et al. 1998; Franceschini et al. 1998).

In deriving number counts of early-type galaxies, morphological classification is needed. MCCD data are classified into early-type and late-type galaxies using the central concentration and the average surface brightness of galaxies (Doi, Fukugita & Okamura 1993). A part of I-band HST data (Abraham et al. 1996a,b) is classified using the central

concentration and the asymmetry of galaxies. Morphological classification of other data is mostly based on eye-ball inspection, though some authors used profile fitting or neural network as well (Casertano et al. 1995; Odewahn et al. 1996; Driver et al. 1998; Franceschini et al. 1998). Morphologically classified K-band counts are available from only two sources (Huang et al. 1998; Franceschini et al. 1998).

We use redshift distributions of the HDF galaxies selected in the I and K bands. The I-band sample is taken from Driver et al. (1998). There are 47 galaxies in $22 < I < 26$. Only 12 out of the 47 galaxies have spectroscopic redshifts, and photometric redshifts (Fernández-Soto, Lanzetta & Yahil 1999) are used for the remaining 35. The K-band sample is taken from Franceschini et al. (1998). There are 34 galaxies in $16.15 < K < 20.15$. Out of the 34 galaxies 14 have spectroscopic redshifts and 20 are assigned photometric redshifts (Franceschini et al. 1998).

3   NORMALISATION OF LOCAL LUMINOSITY FUNCTION

To predict number counts and redshift distributions, the local luminosity function is needed. Recently, the local luminosity function of early-type galaxies has been derived using large redshift surveys. We consider two recent surveys, SSRS2 (Marzke et al. 1998) and 2dF (Colless 1998). The values for M^* and α are different between them ($(\alpha, M^* - 5\log h) = (-1.00, -19.37)$ for SSRS2 and $(-0.486, -19.46)$ for 2dF). We adopt the values given in SSRS2, because the 2dF results are preliminary. However, we confirm that the differences in M^* and α between SSRS2 and 2dF do not significantly affect our results. The measured values for normalisation factor ϕ^* are different by about a factor of 2 between SSRS2 ($0.0086~h^3\mathrm{Mpc}^{-3}$) and 2dF ($0.0044~h^3\mathrm{Mpc}^{-3}$). We do not take these ϕ^* value. Instead, we determine ϕ^* so that the predicted counts at $17.5 < B < 20$ match our MCCD data. The resulting value $\phi^* = 0.0067~h^3\mathrm{Mpc}^{-3}$, which is ~ 1.5 times lower than the SSRS2 value, is adopted.

4   ANALYSIS

4.1   Single burst model of early-type galaxies

We assume pure luminosity evolution for early-type galaxies without the evolution of number or morphology. We compute galaxy evolution using the spectral synthesis code by Kodama & Arimoto (1997) (hereafter KA97). The star formation rate of galaxies ψ is expressed as

$$
\left\{
\begin{array}{ll}
\psi = \frac{1}{\tau_{\mathrm{SF}}} M_{\mathrm{gas}} & (t < t_{\mathrm{gw}}) \\
\psi \simeq 0 & (t \geq t_{\mathrm{gw}})
\end{array}
\right.
\tag{1}
$$

where τ_{SF} is the star formation time scale, t_{gw} is the time when galactic wind blows, and M_{gas} is the gas mass. Luminosity evolution of early-type galaxies, which we are concerned with, is characterized mostly by two parameters, τ_{SF} and t_{gw}. KA97 found that the observed colour-magnitude relation of early-type galaxies in clusters is well reproduced if they adopt $\tau_{\mathrm{SF}} = 0.1~\mathrm{Gyr}$, $t_{\mathrm{gw}} < 0.353~\mathrm{Gyr}$, and the galaxy formation redshift $z_{\mathrm{F}} = 4.5$ ($q_0 = 0.5$, $h = 0.5$). We
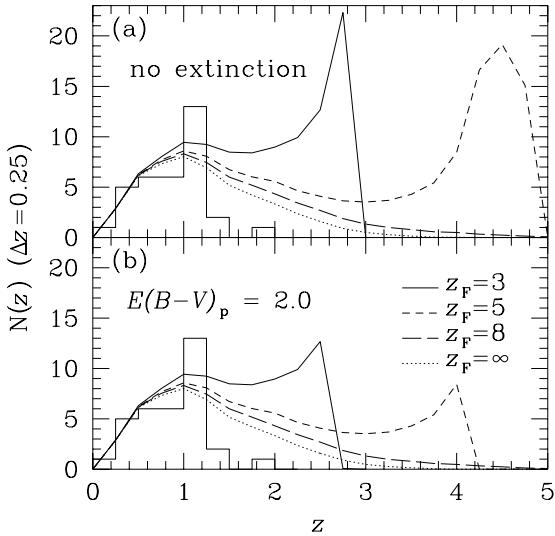
Figure 1. Redshift distribution for the K-band sample $(16.15 < K < 20.15)$ (histograms). Predictions of the single-burst models with $z_F = 3$, 5, 8 and ∞ are shown by lines. Panels (a) and (b) are for no extinction and for the strongest extinction we consider, respectively.

Figure 2. The filled circles indicate a combination of parameters with which the model reproduces observed number counts and redshift distributions for appropriate choice of z_F and $E(B-V)_p$, while open circles show the parameters which do not account for the observations.

limit our discussion to models with $z_F \geq 3$, because early-type galaxies in clusters are suggested to have $z_F \gtrsim 3$ (e.g., Ellis et al. 1997). Hereafter, we call such models with $(\tau_{SF}, t_{gw}, z_F) = (0.1$ Gyr, 0.353 Gyr, $z_F \geq 3)$ the single-burst models. For the initial mass function, we assume a power-law mass spectrum with a slope of $x = 1.10$ in the range of $0.1 M_\odot \leq M \leq 60 M_\odot$. We examine whether the single-burst models can reproduce both observed redshift distributions and number counts. Fig.1(a) compares the observed redshift distribution of the K-band sample (solid histogram) with predictions by a series of single-burst models with different z_F. Four lines correspond to $z_F = 3$, 5, 8 and ∞. It is found that the single-burst models overpredict the number of galaxies at $z \gtrsim 1.4$ irrespective of z_F. In particular, any single-burst model predicts a sharp peak near z_F, because galaxies just after their formation epoch are very bright. Such a peak would disappear if we assume that the formation redshift of early-type galaxies is not a single value but is distributed uniformly in time between $z_F = 3$ and ∞. However, the overprediction at $z \gtrsim 1.4$ still remains, and these models are not consistent with the observations of redshift distribution. We also compare predictions with the observed redshift distribution of I-band sample, and find similar over-predictions. The models shown Fig.1(a) overpredict the K-band counts, but they are marginally consistent with the B-band and I-band counts. However, they are ruled out by the redshift distributions anyway.

4.2 Models with interstellar dust

In order to suppress the overprediction found for the single-burst model, we introduce the effect of dust extinction. The paucity of galaxies at $z \gtrsim 1.4$ may not be due to dust extinction but to some observational selection effects. The dimming of surface brightness by a factor of $(1+z)^4$, for exam-
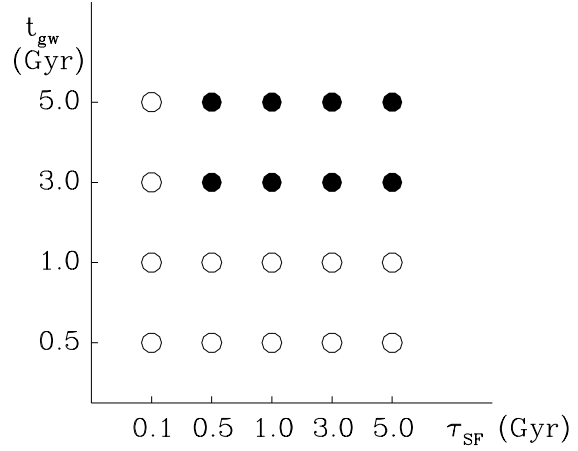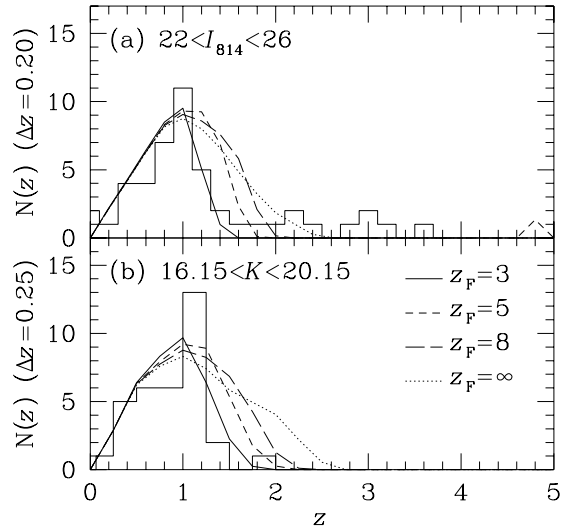

Figure 3. Redshift distributions (histogram) of the I-band sample (a) and the K-band sample (b). Predictions of models using $\tau_{SF} = 0.5$ Gyr, $t_{gw} = 3.0$ Gyr and $E(B-V)_p = 2$ are shown by lines. Four lines correspond to $z_F = 3$, 5, 8 and ∞.

ple, would decrease the detection rate of early-type galaxies at high redshifts. To investigate this effect, we examine the evolution of surface brightness and effective radius of the normal early-type galaxies seen in the local universe on the basis of the single-burst models, and find that most of these galaxies up to $z \sim z_F$ survive the selection criteria for surface brightness and radius set for Franceschini et al.'s (1998) sample, if they are brighter than $K = 20.15$ mag, the limiting magnitude of Franceschini et al.'s (1998) sample. This result is also supported by a similar test using the early-type galaxies of Franceschini et al.'s (1998) sample for which surface brightness, effective radius and redshift are given. Accordingly, the surface brightness selection is not a
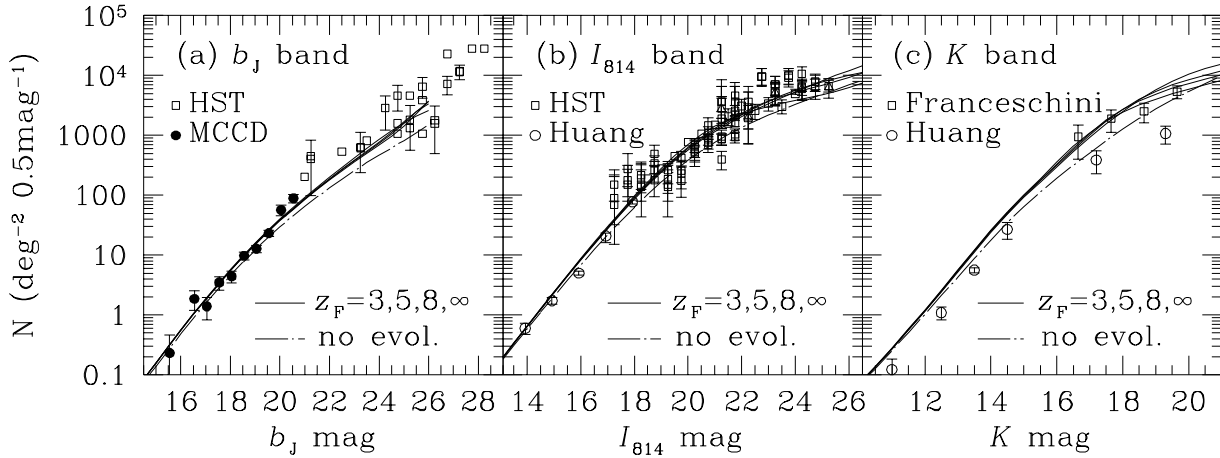
Figure 4. Differential number counts as a function of apparent magnitude. Panels (a), (b) and (c) are for B, I and K band, respectively. Predictions of models using $\tau_{\rm SF} = 0.5$ Gyr, $t_{\rm gw} = 3.0$ Gyr and $E(B-V)_{\rm p} = 2$ are shown by lines. Four lines correspond to $z_{\rm F} = 3$, 5, 8 and ∞. Dash-dotted lines are for no evolution models. See the text (§2) for data sources. MCCD data are used to normalise the local luminosity function. We do not calculate the counts beyond $B > 26$ mag because of the lack of reliable K-correction for redshift above $z = 2$.

problem. Another possible selection effect comes from type classification. Early-type galaxies undergoing intensive star formation, where a significant amount of gas exists, might be classified as late-type galaxies. Such selection effects need further investigation. In this paper, we assume that such selection effects are negligible.

Following Vansevičius, Arimoto & Kodaira (1997), we express the B-band optical depth of a galaxy as

$$\tau(B) = C f_{\rm g} Z_{\rm g} \qquad (2)$$

where $f_{\rm g}$ is the gas fraction of the galaxy, $Z_{\rm g}$ is the metallicity of the galaxy, and C is a constant. The internal extinction in the B band is $A_{\rm B} = -2.5 \log[\exp\{-\tau(B)\}]$ mags. We adopt the extinction curve given in Cardelli, Clayton & Mathis (1989). Then, the colour excess is expressed as $E(B-V) \simeq 0.245\,\tau(B)$. Metallicity $Z_{\rm g}$ increases with time, while $f_{\rm g}$ is a decreasing function of time, with $f_{\rm g} = 0$ at $t \geq t_{\rm gw}$. Therefore, $\tau(B)$ (and thus $E(B-V)$) has a peak value. We treat the peak value, $E(B-V)_{\rm p}$, as a free parameter and change it from $E(B-V)_{\rm p} = 0$ to 2. It should be noted, however, that the nominal peak value obtained from eq.(2) is not necessarily reached at $t \leq t_{\rm gw}$. Actually, $E(B-V) = 0$ for $t \geq t_{\rm gw}$, of course. However, it is the nominal peak value that we change. $E(B-V)_{\rm p} = 2$ corresponds to extraordinary strong extinction.

Fig.1(b) compares the observed redshift distribution of K-band sample (solid histogram) with predictions by models for $E(B-V)_{\rm p} = 2$ with different $z_{\rm F}$. It is found that there still remains the overprediction. This is because the extinction, though very strong, works only in a very short period ($\lesssim 0.3$ Gyr) due to the small values for $\tau_{\rm SF}$ and $t_{\rm gw}$. The models shown Fig.1(b) are more or less consistent with the number counts. However, they are also ruled out by the redshift distributions.

If larger values are adopted for $\tau_{\rm SF}$ and $t_{\rm gw}$, the duration when extinction works becomes longer. In order to investigate this effect, we change $\tau_{\rm SF}$ and $t_{\rm gw}$ as free parameters in $0.1 \leq \tau_{\rm SF} \leq 5.0$ Gyr and $t_{\rm gw} \geq 0.5$ Gyr, respec-

tively, and examine whether there exists a combination of $\tau_{\rm SF}$ and $t_{\rm gw}$ that does not overpredict galaxies at $z \gtrsim 1.4$ and is consistent with observed number counts. We regard a model to be consistent with the observations if the model reproduces both observed number counts and redshift distributions for appropriate choices of $z_{\rm F}$ and $E(B-V)_{\rm p}$. Results are shown in Fig.2, where the filled circles indicate a combination of parameters which is consistent with the observations while open circles show the parameters which do not account for the observations. We confirm that the combinations indicated by filled circles give $B - V$ colours at $z = 0$ which are consistent with that of local early-type galaxies ($0.8 < B - V < 1.1$; Fukugita, Shimasaku & Ichikawa 1995). As an example, we present the predicted redshift-distributions using $\tau_{\rm SF} = 0.5$ Gyr, $t_{\rm gw} = 3.0$ Gyr and $E(B-V)_{\rm p} = 2$ in Fig.3. We regard the cases when $z_{\rm F} = 3$ in Fig.3 as being consistent with the observation. This combination is also consistent with the observed number counts as shown in Fig.4. In Fig.3(a), there are several galaxies at $z \gtrsim 1.5$ in the I band sample, while the models predict no galaxies there. We do not think, however, that this discrepancy is significant. It is plausible that the amount of dust extinction of actual galaxies has various values, unlike our models that assume the same dust extinction for all galaxies. A small fraction of weaker extinction galaxies could explain those galaxies at $z \gtrsim 1.5$.

We find from Fig.2 that if $\tau_{\rm SF} \geq 0.5$ Gyr and $t_{\rm gw} > 1.0$ Gyr are taken, the predicted number counts and redshift distributions are consistent with the observations. However, $E(B-V)_{\rm p} \geq 1$ is needed for all cases. This value is much larger than the colour excess of Lyman break galaxies at $z \simeq 3$, $E(B-V) \sim 0.3$, found by Sawicki & Yee (1998). In Fig.2, we show the result only for the case of $t_{\rm gw} \leq 5.0$ Gyr. In fact, we investigate the case that galactic wind does not blow, and find that the predicted number counts and redshift distributions are consistent with the observations as well. However, colours of these galaxies at $z = 0$ are inconsistent with observations.

It is interesting to examine whether or not the models indicated as the filled circles in Fig.2 are consistent with the observations of early-type galaxies in clusters as well. We find that these models are marginally consistent with the observed evolution of luminosity and mean colours of cluster early-type galaxies up to $z = 1.27$, the redshift of the most distant cluster at present. (We cannot discuss the slope and scatter of the colour-magnitude relations of cluster early-type galaxies, because we assume here that all early-type galaxies have the same age and metallicity.) At $z > 1.27$, however, these models predict quite different evolution of luminosity and colours from that based on the single-burst models, due to the effect of dust extinction.

As seen in Fig.4(c), K-band number counts of Huang et al. (1998) at $17 \lesssim K \lesssim 19$ are lower than those of Franceschini et al. (1998) by more than a factor of three. The reason for this discrepancy is not clear for us. However, K-band number counts of Huang et al. (1998) in bright magnitude, $K \lesssim 14$, where the effect of galaxy evolution is negligible, are also lower than the prediction, though the predictions for B and I counts at bright magnitudes are in good agreement among different observations. Because we cannot reproduce Huang et al.'s (1998) data for K-band counts, we ignore them in comparing with models.

5   CONCLUSION AND DISCUSSION

We investigate pure luminosity evolution models for early-type galaxies which do not exhibit either number density change or morphology transition, and examine whether these models are consistent with observed number counts and redshift distributions. We summarize our findings as follows:

(i) We find that single-burst models are inconsistent with observed redshift distributions irrespective of z_F (if $z_F > 3$), due to the overpredictions of galaxies at $z \gtrsim 1.4$, even if dust extinction which is in effect during star formation is taken into account.

(ii) In order for dust extinction to be more effective, we change τ_{SF} and t_{gw} as free parameters over the ranges of $0.1 \leq \tau_{SF} \leq 5.0$ Gyr and $t_{gw} \geq 0.5$ Gyr, respectively, and examine whether there exists a combination of τ_{SF} and t_{gw} that does not overpredict galaxies at $z \gtrsim 1.4$ and is also consistent with observed number counts. We find that models with $\tau_{SF} \geq 0.5$ Gyr and $t_{gw} > 1.0$ Gyr can be made consistent with the observed redshift distributions and number counts, if we introduce strong extinction ($E(B-V)_P \geq 1$).

Our finding that the single burst models cannot express the evolution of field early-type galaxies well is not new. Franceschini et al. (1998) analysed K-band number counts and redshift distribution for field early-type galaxies, and found that models which assume the duration of star formation to be about 3 Gyr with dust extinction during star formation are preferred. Our study not only confirms their results but also extends their study: using B-, I- and K-band number counts and I- and K-band redshift distributions, we systematically study what combinations of τ_{SF} and t_{gw} can reproduce the observation. He & Zhang (1999) presented a redshift distribution for galaxies limited to $22.5 < b_j < 24.0$ and $B - K > 5.5$, which they considered to be early-type

galaxies, and compared it with the predictions of single-burst models and models with $\tau_{SF} = 1$ Gyr. They found that these models overpredict the observed redshift distribution at $z > 0.8$, and suggested that number evolution may be essential for early-type galaxies. However, we confirm that using our models with strong dust extinction, the overpredictions of the redshift distribution can be removed. Driver et al. (1998) analysed I-band number counts and redshift distribution for early-type galaxies and found that the single-burst models overpredict galaxies in redshift distribution, which is consistent with our results. Im et al. (1999) analysed I-band redshift distribution for early-type galaxies and found that observations are consistent with those expected from passive luminosity evolution or are only in slight disagreement with the nonevolving model. However, their results are not in conflict with ours, because the redshift distributions they analysed are at $I < 21$, where most galaxies are at $z < 1.0$.

It is true that the pure luminosity evolution models with dust extinction are not the only model which reproduces the observed number counts and redshift distributions. Models with number density change or morphology transition, such as those based on hierarchical clustering scenarios (e.g., Kauffmann, White & Guiderdoni 1993; Baugh, Cole & Frenk 1996) may account for the observations. However, we can at least conclude that early-type galaxies in the field environment have a different evolution history from the single-burst models, if the observational selection effects are not significant.

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